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DUAL CAVITY SCRAMJET OPERABILITY AND PERFORMANCE STUDY (POSTPRINT)

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Taitech, Inc.

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14. ABSTRACT
The purpose of this study is to compare the operability and performance of a dual cavity supersonic combustor with that of a single cavity over various flight conditions, equivalence ratios, and fuel injection schemes. Experimental and numerical approaches will be used to explore the effects of various fueling schemes for both single and dual cavities. Discrete flight conditions from Mach 3.5 to 5.0 at flight dynamic pressures from approximately 500 to 2000 psf were studied. The objectives of this study include: 1) investigate the effects of adding a second cavity to a scramjet flow path, and 2) determine and analyze the performance and operability of the dual cavity for various conditions. Measurements including streamwise pressure distribution profiles, peak and exit pressure ratios, and stream thrust have been obtained. Results suggest a significant increase in performance using a dual cavity flame holder.

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Dual Cavity Scramjet Operability and Performance Study

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Many studies have been conducted showing the benefits of using cavity flame holding and axial fuel distribution techniques to improve combustion in supersonic flow paths. These studies have primarily focused on using a single cavity within the flow path. Dual flame holding cavities may provide additional benefits and increased combustor performance. The purpose of this study is to compare the operability and performance of a dual cavity supersonic combustor with that of a single cavity over various flight conditions, equivalence ratios, and fuel injection schemes. Experimental and numerical approaches will be used to explore the effects of various fueling schemes for both single and dual cavities. Discrete flight conditions from Mach 3.5 to 5.0 at flight dynamic pressures from approximately 500 to 2000 psf were studied. The objectives of this study include: 1) investigate the effects of adding a second cavity to a scramjet flow path, and 2) determine and analyze the performance and operability of the dual cavity for various conditions. Measurements including streamwise pressure distribution profiles, peak and exit pressure ratios, and stream thrust have been obtained. Results suggest a significant increase in performance using a dual cavity flame holder.

Nomenclature

I-2	=	Injector 2 (top wall, upstream)
I-4	=	Injector 4 (bottom wall, upstream)
I-5	=	Injector 5 (top wall, downstream)
I-7	=	Injector 7 (bottom wall, downstream)
ER	=	Equivalence ratio
M	=	Mach number
L/D	=	Ratio of length of cavity to depth of cavity
Q	=	Dynamic pressure

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I. Introduction

WHILE there are many challenges in developing a hypersonic propulsion system, one of the most important involves the design of the combustor. For successful operation at hypersonic flight speeds, the air flow through the engine must be maintained at supersonic conditions. The supersonic conditions result in flow path residence times on the order of 1 ms. In this short amount of time, the fuel must be injected, mixed with air, and burned. Many studies have been conducted that attempt to overcome the challenges presented by this short residence time. Previous work shows a cavity placed in a scramjet flow path will provide a recirculation zone for improved fuel-air mixing and flame holding.[1-8] This low-velocity area created by the cavity gives the necessary additional time for combustion to occur.

The operability and control of the shock train is a concern in dual-mode scramjet combustors. One way to control efficient engine operation is to vary the combustor area distribution over changing flight conditions. However, the use of a variable-geometry combustor leads to even more challenges.[9] Therefore, a fixed-geometry combustor is usually used. In order to control engine performance and operability in this case, the common approach is to use axial staging of fuel injection. By controlling the axial fuel distribution and axial heat release, the pre-combustion shock train can therefore also be controlled.

Many studies have been conducted showing the benefits of using these cavity flame holding and axial fuel distribution techniques.[3,4,10,11] However, these studies have only looked at using a single cavity within the flow path. Dual flame holding cavities may provide additional benefits and increased combustor performance.[12] This research investigates the potential use of a second cavity, which may allow the flame to couple across the entire height of the flow path. Expected shortcomings of the dual cavity may present more unique challenges, such as increased aerodynamic drag. This work will study the advantages and disadvantages of using a dual cavity flame holder.

II. Experimental Method

The experiment was performed in the Research Cell 18 direct-connect supersonic combustion flow facility at the Air Force Research Laboratory, Wright-Patterson Air Force Base. This facility was designed for fundamental studies of supersonic reacting flows using a continuous-run direct-connect open-loop airflow supported by the Research Air Facility.[10] The test rig consists of a natural-gas-fueled vitiator, interchangeable facility nozzle (Mach 1.8 and 2.2 currently available), modular isolator, modular combustor, and exhaust pipe, as illustrated in Figure 1. There is also a short truncated nozzle located directly between the combustor and the exhaust pipe.

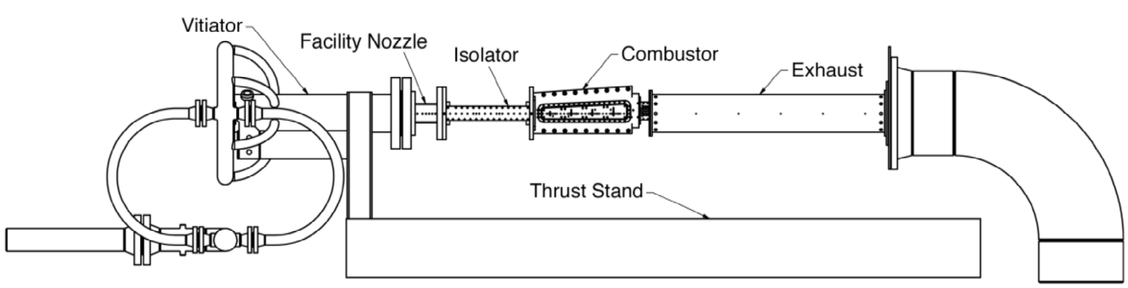

Figure 1. Schematic of Research Cell 18 combustion facility at WPAFB.

The rig is mounted to a thrust stand capable of measuring thrust up to 2000 lbf. A series of compressors capable of providing up to 30 lb/s of air, with total pressures and temperatures up to 750 psia and 1600 R, respectively, supply air to the facility. An exhaust system with a pressure as low as 3.5 psia lowers and maintains the backpressure for smooth starting and safe operation. Combined with currently available Mach 1.8 and 2.2 facility nozzles, the air vitiator was fine-tuned to simulate discrete flight conditions from Mach 3.5 to 5.0 at flight dynamic pressures up to 2000 psf. The relatively low simulated flight Mach numbers represent the scramjet takeover conditions, at which dual-mode combustion takes place. Table 1 below shows seven cases, each with a single and dual cavity run, that were chosen for complete analysis. The fuel injectors used (I-2, I-4, I-5 and I-7) are further explained below.

Case	Cavity	Q (psf)	Flight M	ER I-2	ER I-4	ER I-5	ER I-7	Total ER
1	Single	500	4.5	0.6				0.6
1	Dual	500	4.5	0.6				0.6
2	Single	500	4.5	0.9				0.9
2	Dual	500	4.5	0.9				0.9
3	Single	500	4.5	1.1				1.1
3	Dual	500	4.5	1.1				1.1
4	Single	500	4.5	0.6				0.6
4	Dual	500	4.5	0.3	0.3			0.6
5	Single	500	4.5	0.6				0.6
5	Dual	500	4.5	0.3	0.3			0.6
6	Single	1000	5.0	0.6				0.6
6	Dual	1000	5.0	0.3	0.3			0.6
7	Single	1000	5.0	0.45		0.45		0.9
7	Dual	1000	5.0	0.225	0.225	0.225	0.225	0.9

Table 1. Simulated flight conditions of the present study.

The scramjet flow path of the present study consists of a heat-sink rectangular isolator and a water-cooled rectangular combustor featuring two recessed cavity flame holders and flush-wall low-angle injectors. The isolator has a rectangular cross-section with a height of 1.5 in, a width of 4.0 in, and a length of 25.75 in. The combustor has a total length of 36 in and a constant divergence angle of 2.6 degrees at the top wall. However, there is no divergence angle at the bottom wall. A thermal barrier coating covers the interior surface of the entire flow path. Two water-cooled combustor sidewall inserts can be replaced with quartz windows for flame visualization and optical measurements. The recessed cavity flame holders are located on the bottom wall and the divergent top wall, as shown in Figure 2 (flow from left to right). These flame holders span the entire flow path width and have a forward-facing ramp to effectively interact with the shear layer originating from the cavity leading edge. Two conventional spark plugs, located at the base of the cavities, are used as the baseline ignition source.

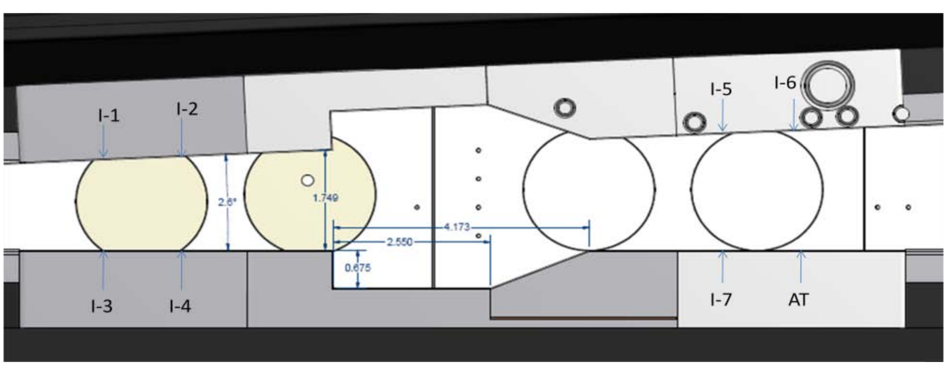

Figure 2. Side view of the flow path showing the dual flame holding cavities on the top and bottom walls.

There are eight cavity fuel injectors located at each of the cavity ramps to provide cavity fuel injection parallel to the cavity base. Four banks of injectors, two banks each on the top and bottom walls were designed to provide various fueling options. Fuel injectors I-1 and I-2 are low-angle injectors located forward of the cavity on the top side. I-3 and I-4 are directly below on the bottom side. I-5 and I-6 are secondary normal injectors located on the top

side downstream of the cavity. Directly below I-5 sits another normal injector (I-7) on the bottom side with an air throttle (AT) section behind it. The design for the gaseous fuel injectors was adopted from the study of Mathur et al.[11] with appropriate scaling of the orifice size. All orifices have the same diameter. The study relied on unheated ethylene as the fuel for both main injectors and cavity fueling ports.

Pressure taps and thermocouple ports were strategically positioned throughout the entire rig for instrumentation and health monitoring. The data acquisition system consists of a CAMAC-based crate (128 analog inputs, 16 analog outputs, 48 digital inputs and 32 digital outputs channels), a 256-channel electronic pressure scanning system (Pressure Systems Incorporated) and a 64-channel thermocouple scanning system (Scanivalve Incorporated).

III. Results and Discussion

A. Pressure Profiles

Pressure profiles for select cases are discussed below. Figure 3 shows the axial pressure data from the single cavity run of case 5. The red line is the pressure profile when only air is flowing and no fuel is being injected, i.e. the tare case. The blue line shows the pressure during the period of steady state combustion. The top of the flow path components, including the isolator, the combustor with cavity, and the truncated nozzle, are represented by the solid black line in each of the following pressure plots. The solid blue line underneath it represents the bottom of the flow path used for the single cavity configuration. When used, the bottom cavity is shown in red.

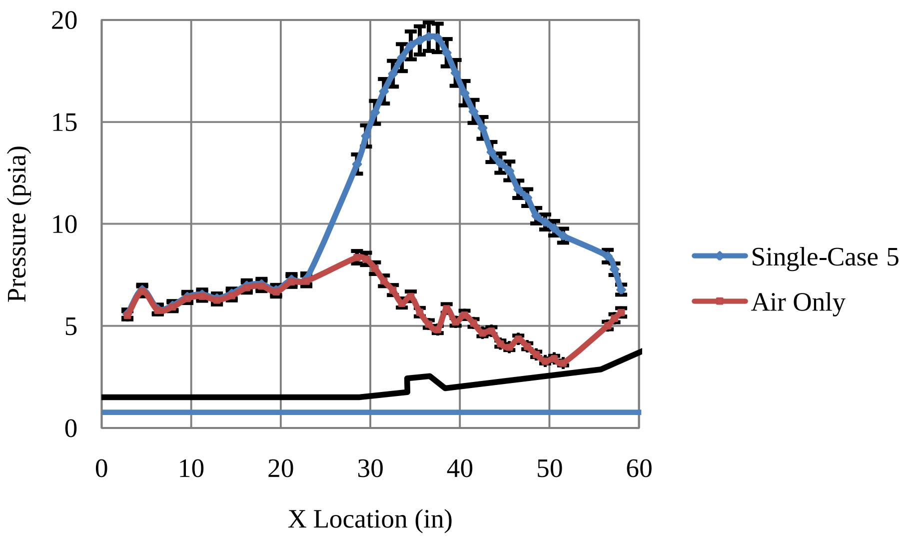

Figure 3. Pressure versus axial position with error bars.

During combustion, the increase in pressure occurs at the beginning of the shock train. If the shock train moves too far upstream in the isolator it would cause an inlet unstart. The unstart would be seen on the pressure profile graph as a separation between the two lines occurring within the first two pressure points at x = 2.9 and x = 5.4 inches. That is, the tare (air only) and combustion profiles would be separated. Here, tare and combustion are identical until x = 24. If only one, or none, of the first two points overlap, the run would be considered an unstart. This will be a primary method of characterizing the operability of the flow path. These pressure profiles help to explain what is occurring throughout the flow path. The large pressure near the flame holder is due to significant heat addition in that area. The increased pressure from the divergent wall starting at approximately x = 40 yields significant thrust due to the change in area. The tare profile shows separation of the flow near the truncated nozzle. The flow is detaching from the wall as it hits the increased area at the entrance to the truncated nozzle causing the pressure to rise quickly. The combustion flow at this point does not separate due to the increased pressure from the combustion process. Figure 3 also shows a 3.5% uncertainty due to systematic and random errors.[13] The variations

in the air only run throughout the combustor are not due to errors. These fluctuations are caused by a shock wave off the back of the cavity and an expansion wave off the front of the cavity.

Figure 4 shows the single and dual cavity runs from case 1. Each of these runs was conducted with the M = 2.2 facility nozzle with a nominal equivalence ratio of 0.6. The gaseous ethylene fuel was injected from I-2 on the top side of the flow path, upstream of the cavity, in both runs. The dual cavity run shows a slightly more upstream shock position. It also has an increased peak pressure and slightly higher exit pressure. An increase in pressure such as this is usually due to an increase in heat release as a result of better combustion.

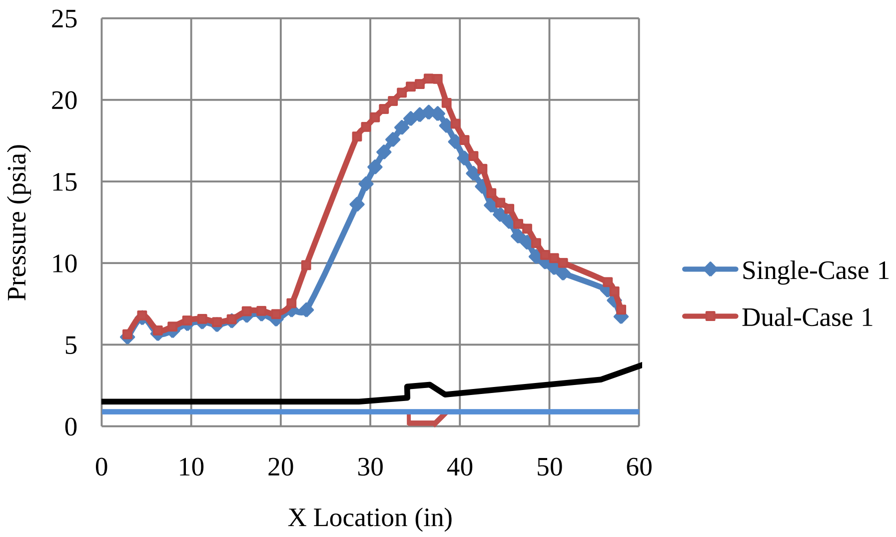

Figure 4. Case 1 pressure profile with a nominal ER of 0.6.

Figure 5 shows the pressure profiles for case 2. These runs represent the same flight conditions as case 1, but had equivalence ratio set points of 0.9. The actual run ERs were slightly lower at 0.808 for the single cavity run and 0.869 for the dual cavity run, both with I-2 only fuel injection.

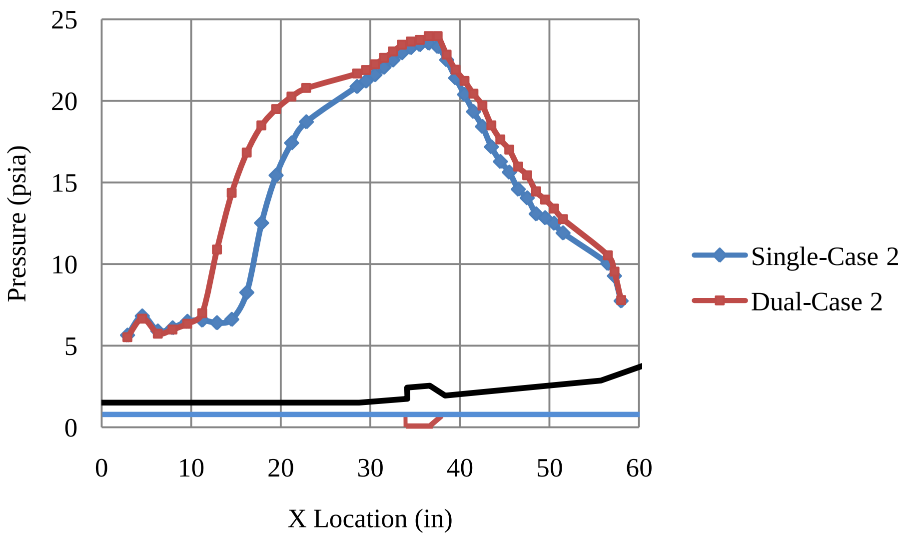

Figure 5. Case 2 pressure profile with a nominal ER of 0.9.

The graph shows the same trends as for case 1, but with an upstream shock location that is further forward. These runs have the first five pressure taps overlapping, indicating neither of them has the potential of an unstart

issue. The dual cavity again shows a slightly higher peak pressure as well. Although, the equivalance ratio is slightly higher for the dual cavity, which could account for a small portion of the dual cavity having a shock position further upstream and higher peak pressure. However, there is a substantial difference in the shock position of nearly four inches. This is not caused purely from the difference in fueling. Therefore, the dual cavity is providing some additional performance capabilities.

The equivalence ratios for case 3 were set even higher with a value of 1.1. The actual ERs were 0.949 for the single cavity and 1.034 for the dual cavity flow path. Figure 6 shows the dual cavity run created an unstart condition. The first two points are separated from their position in the single cavity case. When an unstart occurs, there is no guarentee the test conditions were ever met. The unstart also provides information on the operability of the dual cavity. Thus far, with I-2 injection, the dual cavity will operate at equivalence ratios between approximately 0.58 and 0.87, but not up to 1.03. This could provide negative consequences as equivalence ratios above 1.0 are often neccessary for periods of rapid acceleration.

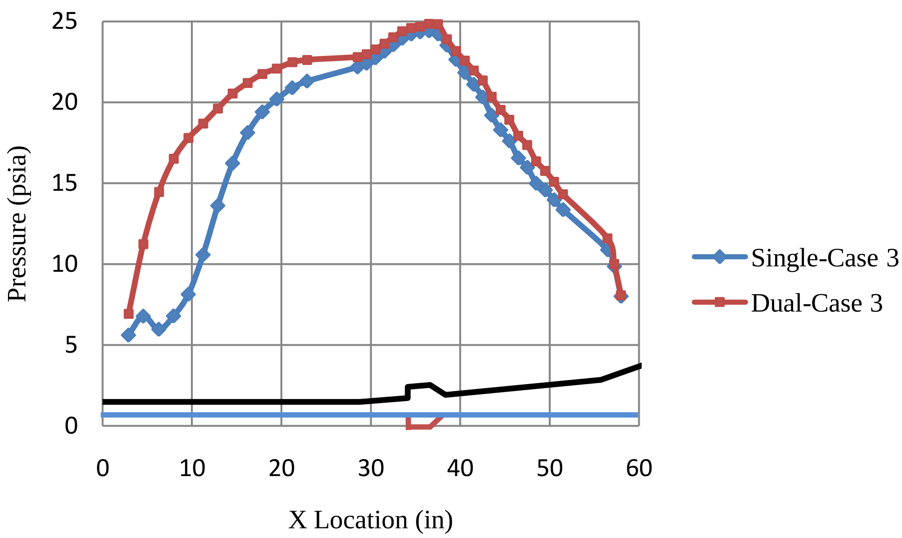

Figure 6. Case 3 pressure profile with a nominal ER of 1.1.

Case 4 results are shown below in Figure 7. In this case, the single cavity was fueled from I-2 only while the dual cavity utilized both I-2 and I-4 injection sites. The single cavity run had an equivalence ratio of 0.533. The dual cavity had an I-2 ER of 0.293 and an I-4 ER of 0.234 for a total of 0.527. The absolute fuel flow into the combustor varied slightly between the single and dual cavity runs with rates of 0.069 and 0.073 lb_m/sec, respectively. It is obvious from the pressure profile graph that the dual cavity flow path provides a much greater pressure rise than the single cavity. In the dual cavity run, ignition occurs at both the top and bottom flame holders. This results in significant heat release from both causing a large overall pressure rise. The shock position is also further upstream, but not to the point of unstart.

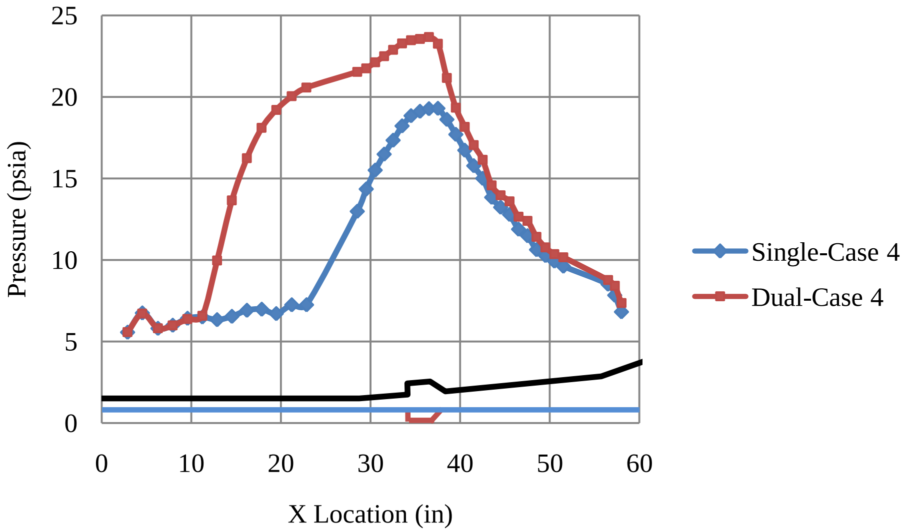

Figure 7. Case 4 pressure profile (ER=0.53).

The final pressure profile comparison is for case 7 and is shown in Figure 8. This case utilizes both upstream and downstream fueling. The single cavity run has fuel split between I-2 and I-5 and has a total equivalence ratio of 0.78. The dual cavity run uses I-2 and I-4 upstream and I-5 and I-7 downstream of the cavities and has a total ER of 0.836. This case shows the greatest difference in shock position and peak pressures between the two runs of any of the cases. The fueling scheme from the dual cavity run provides a significant advantage in pressure increase over the single cavity. However, while the dual cavity run is not considered an unstart, it is very close. Any increase in fueling would likely push the shock upstream and cause it to unstart.

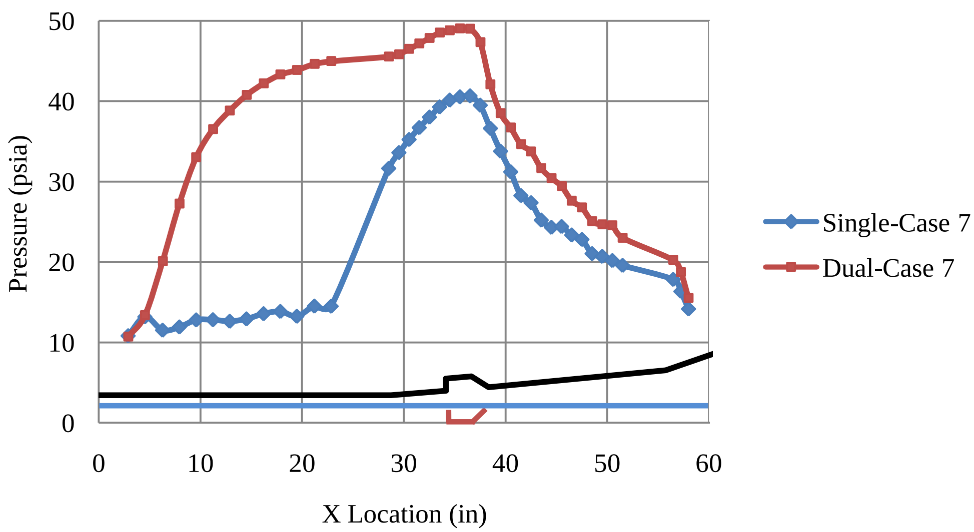

Figure 8. Case 7 pressure profile (ER=0.8).

B. Pressure Ratios

Figure 9 below shows the peak pressure ratios for each run. The peak pressure ratio is determined by dividing the peak pressure from the flow path by the lowest pressure. The highest pressure is located in the cavity, while the lowest pressure is always from the first pressure tap in the isolator.

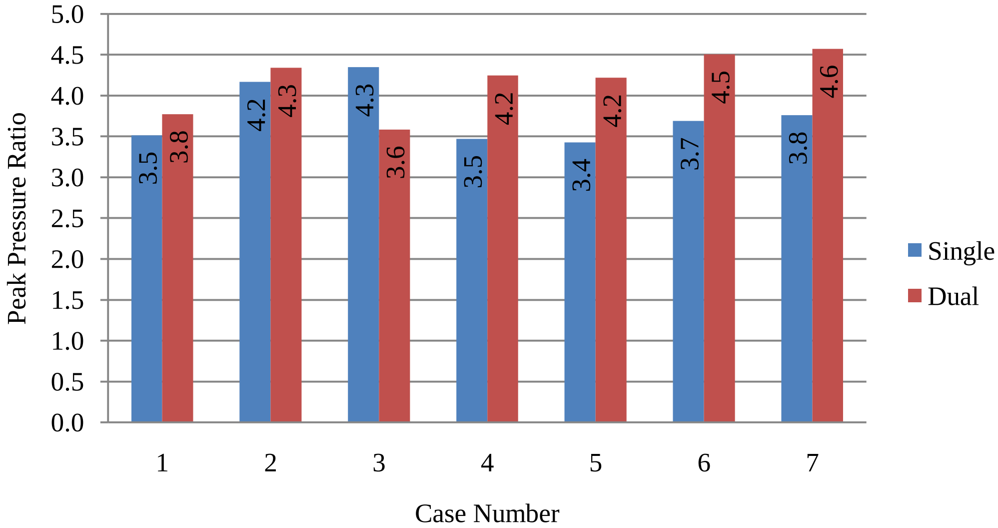

Figure 9. Peak pressure ratios.

Each case shows a higher peak pressure ratio from the dual cavity flow path except for case 3. This is likely due to the unstart phenomenon, as discussed earlier. Cases 1 and 2 have only an 8.6% and 2.4% increase, respectively. However, cases 4-7 that have fueling from both the top and bottom sides show a significant increase of 20% or more. This increase in peak pressure ratio is due to a greater heat release, suggesting the dual cavity is providing better combustion relative to the single cavity combustor for a given fueling level.

The combustor exit pressure ratio is another way to characterize performance changes relative to the cavity configurations. It is found by taking the pressure reading from the last pressure tap in the combustor and dividing it by the lowest pressure found at the beginning of the isolator. The combustor exit pressure ratios are shown in Figure 10.

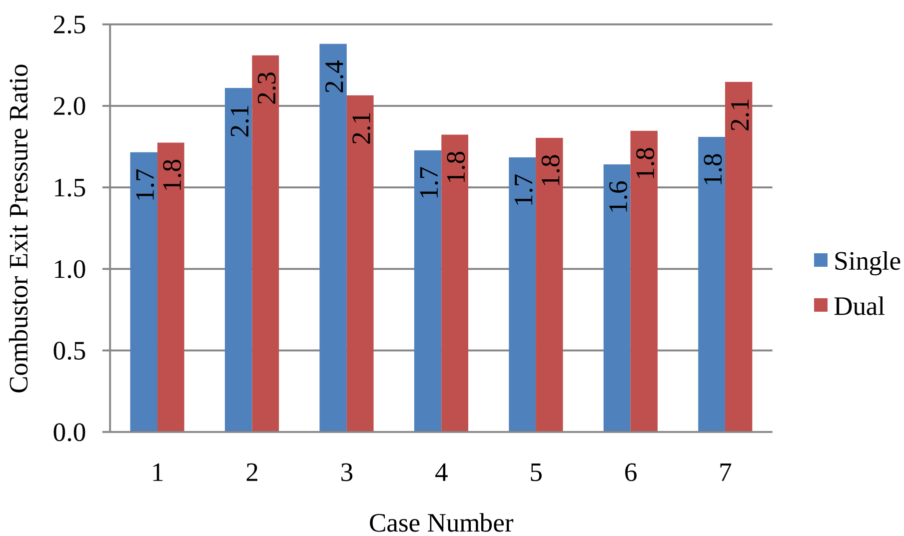

Figure 10. Combustor exit pressure ratios.

Each case shows a slightly higher ratio for the dual cavity runs. The only exception is case 3 and is due to the unstart. There is a difference of 5-17% for each case. For the same combustor geometry, isolator inlet conditions,

and fuel flow rate, higher exit pressures mean greater heat release. Therefore, the increase in exit pressure is further evidence that the dual cavity may be providing better performance than the single cavity flow path.

C. Stream Thrust

Another way of determining performance is by comparing stream thrust. It is found using the momentum equation for control volume analysis:

$$ST = F + P_{amb} A_E + (P_{amb} - P_{base}) A_{base} \tag{1}$$

where F is the load cell force, P_{amb} is the ambient pressure, A_E is the exit area, and P_{base} is the average of the twelve base pressures from the end of the truncated nozzle. The exit area had a value of 17.132 in^2 and the base area was 23.39 in^2. The stream thrust values are shown in Figure 11.

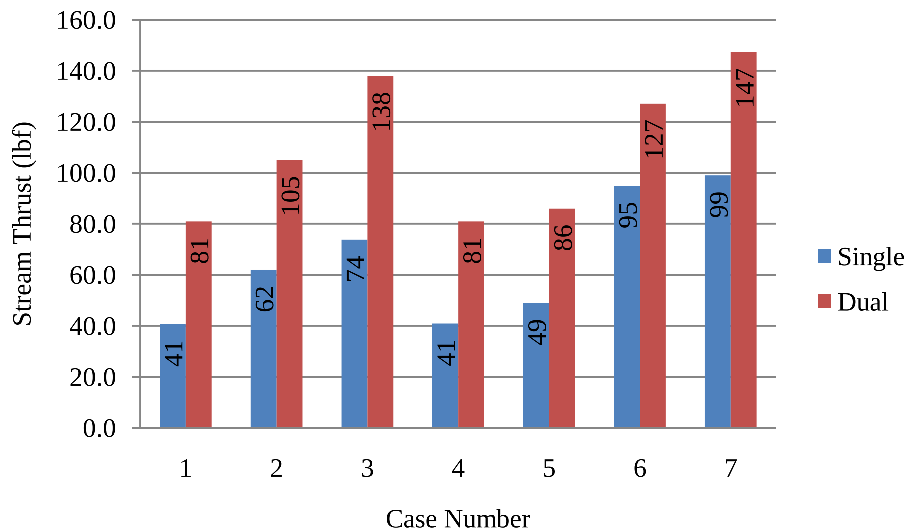

Figure 11. Stream thrust comparison.

Each case has a stream thrust significantly higher for the dual cavity than for the single cavity. The dual cavity has an average of over 72% higher stream thrust.

To further verify these results, the stream thrust values were normalized to account for differences in the fuel flow rate between the single and dual cavity runs for each case. The normalization was accomplished by dividing the stream thrust by the total fuel mass flow rate. These normalized stream thrust values are shown in Figure 12.

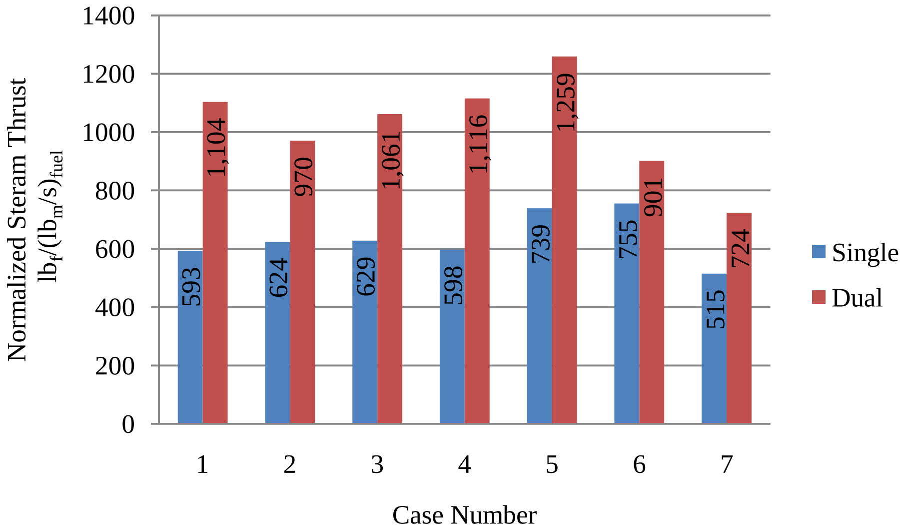

Figure 12. Normalized stream thrust comparison.

The normalized stream thrust values show the same trend as the original stream thrust comparison. Each dual cavity run has a significantly higher value than the single cavity. Therefore, these differences in stream thrust are due to increased performance, not differences in fuel flow rates. The increase of stream thrust with the dual cavity is further evidence that the effect of adding the additional flame holder is to provide better performance.

D. Operability

Figure 13 shows how the position of the shock train relates to the total equivalence ratio. This is the primary determinant of operability. The position of the shock train is determined to be the first pressure tap where the ratio of its value divided by the tare value at the same location is equal to or greater than 1.1.

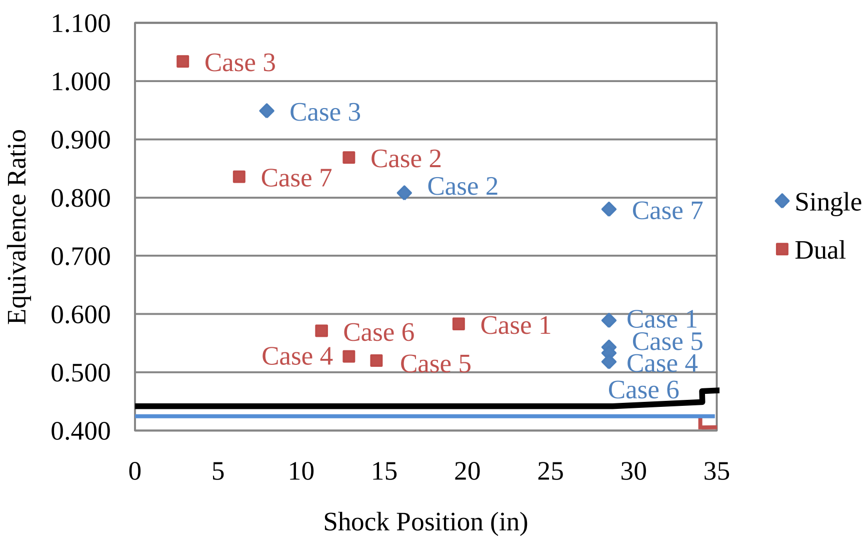

Figure 13. Shock position versus total equivalence ratio.

Each run with the dual cavity configuration has a shock position further upstream in the isolator than the corresponding single cavity flow path. This result suggests the dual cavity has a smaller range of operability and is more likely to unstart as the equivalence ratio is increased. However, by varying the fueling conditions the dual

cavity provides similar stream thrusts while maintaining downstream shock positions. For example, the dual cavity run from case 4 provides similar stream thrust as that of the single cavity run of case 3. Figure 13 shows that the shock position from the dual cavity run of case 4 is downstream relative to that of the single cavity run of case 3. This demonstrates the superior capability of the dual cavity to provide increased stream thrust while maintaining a downstream shock position. In addition, the dual cavity run of case 4 is achieved using an equivalence ratio of 0.6 while the single cavity run of case 3 has an equivalence ratio of 1.1. Therefore, the dual cavity also requires less fuel than the single cavity in order to produce a similar amount of stream thrust.

E. Numerical Assessments

The experimental results provide great insight into the combustion taking place in a dual cavity flow path. However, there are limitations to the instrumentation and flow visualization of this setup. Computational fluid dynamics (CFD) can help to further understand what is taking place inside the flow path.

CFD++, developed by Metacomp Technologies, was used for this study.[14] A cubic κ-ε turbulence model and a gaseous ethylene chemistry kinetic model, based on the Princeton University 22-species reduced kinetic mechanism, was also used. A no-slip, adiabatic boundary condition was imposed on the solid walls. Due to the symmetry assumption at the center plane, only half of the scramjet isolator/combustor configuration was computed in this study.

There are a few issues contributing to discrepancies between the numerical simulations and experimental data, including the adiabatic wall assumption, turbulence modeling, gaseous ethylene chemistry model and surface roughness. In the experiment, the scramjet flow path consists of a heat-sink rectangular isolator and a rectangular combustor. The interior surfaces of the entire flow path are covered with thermal barrier coating for additional thermal protection. This coating has a relatively rough surface. In addition, the combustor is water-cooled to protect the integrity of the material.

Since CFD uses the assumption of adiabatic boundary conditions, the numerical simulations do not account for the heat loss due to the water-cooled panels in the combustor section. In general, the numerical results will tend to over-predict the location of the leading edge of the shock train. However, the numerical results could provide the general trends and a better understanding of the flow physics.

The CFD pressure profiles for two runs are compared to the experimental results in Figure 14. The single cavity run is from case 1 with an equivalence ratio of 0.6 and I-2 fueling. The dual cavity run is from case 4 and has the same ER, but utilizes I-2 and I-4 fuel injection.

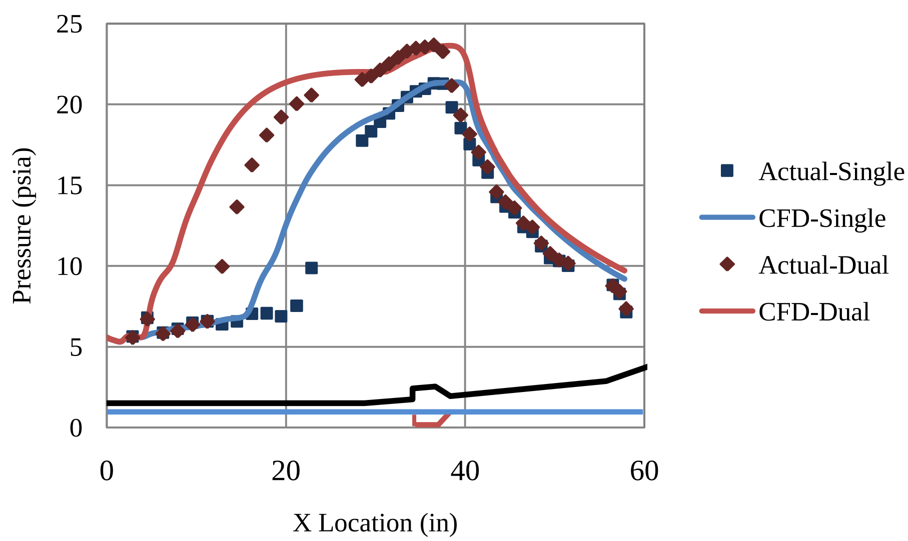

Figure 14. Experimental and CFD comparisons.

The CFD shows very similar peak pressures as compared to the actual data. The CFD also shows the position of the shock further upstream, but the trends between CFD and the experimental profiles are very close. The overall trends are of greater importance in this study then actual temperatures and pressures. Therefore, the CFD is used as a supplement to the experimental results to further analyze the dual cavity performance.

In order to better understand why the dual cavity may be heating when the fuel is being injected from only I-2 on the top side, the equivalence ratio was studied. Figure 15 shows how the equivalence ratio may be changing throughout the flow path.

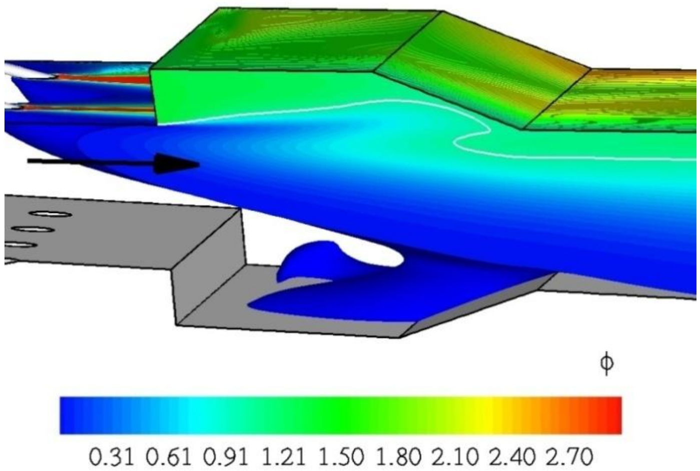

Figure 15. CFD equivalence ratio for the dual cavity run of case 1.

The figure shows small amounts of fuel are reaching the bottom cavity. While the amount of fuel in the lower cavity would be very small, it is possible there would be enough for the cavity to ignite and for combustion to occur. CFD estimated the local equivalence ratio in the bottom cavity was approximately 0.06, well within the range for combustion to occur at this condition.

CFD can also provide estimated temperatures throughout the flow path. The CFD assumes adiabatic walls, so these temperatures are much higher than what the experimental results would show. However, the trends are the same. Figure 16 shows the predicted static temperatures for the dual cavity run of case 1.

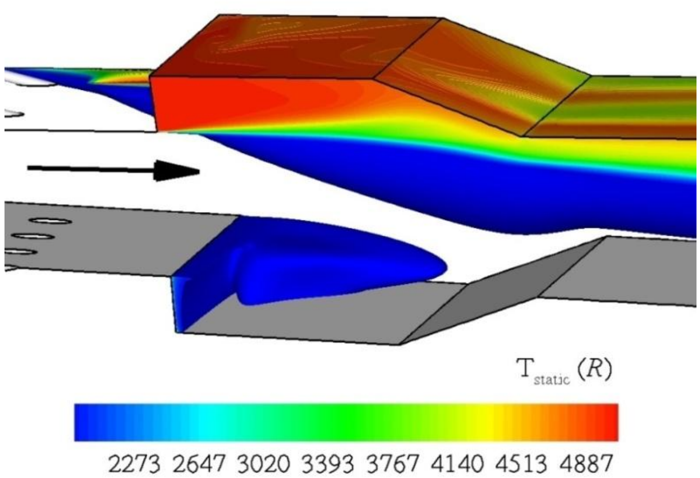

Figure 16. CFD temperature for the dual cavity run of case 1.

The spark plug in the bottom cavity was simulated using a heat source on the cavity front wall. The figure shows the highest temperatures occur in the top cavity as expected. However, there is still a temperature increase in the bottom cavity. It is expected that the heat rise is the bottom cavity is due to a small amount of combustion heating. This can be seen by the small concentration of OH in the bottom cavity in Figure 17.

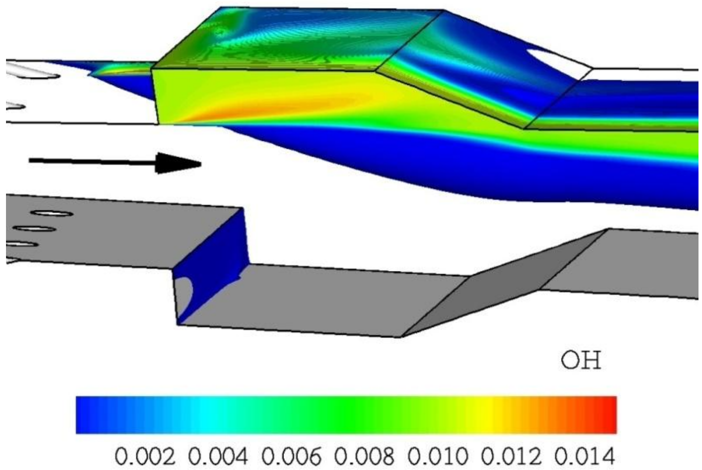

Figure 17. CFD OH concentration for the dual cavity run of case 1.

The CFD analysis suggests the increase in performance seen in the experimental results is likely due to a small amount of combustion taking place in the lower cavity. The combustion then causes a temperature rise and higher stream thrust values for the dual cavity. This is true even when fuel is only being injected from the top side of the flow path. A high speed image of the dual cavity run of case 1 with only I-2 fuel injection is shown in Figure 18.

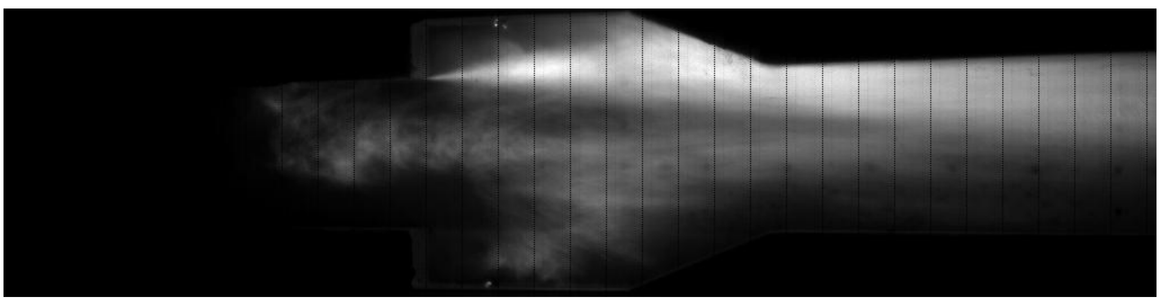

Figure 18. High speed image (800 frames per second) of dual cavity with I-2 fuel injection.

This photograph clearly suggests heat release in both cavities. While there is only fuel from the top side, the CFD showed it is possible for fuel to be entrained into the bottom cavity, most likely through sidewall interaction. There are spark plugs in both cavities which allow them to ignite simultaneously, even when fuel is only being injected from I-2. It is likely that fuel is traveling down the sidewall of the combustor where there are lower flow velocities. Small amounts of fuel are creeping into the cavity, being ignited, and burning for short periods of time. The flow in this area varies greatly with time, but this photo is evidence that it is possible for the bottom cavity to ignite with only I-2 fuel injection. This photo further explains why the dual cavity provides better performance, higher pressures, and higher stream thrusts as compared to similar conditions with only a single cavity flame holder.

F. Visualization

The flow path was fitted with a quartz window in the combustor sidewall for one set of experiments. This allowed flame emission images to be captured through digital and high speed photography. Similar fueling conditions were conducted as in the data runs described in Table 1. Figure 19 shows digital photographs of two dual cavity runs.

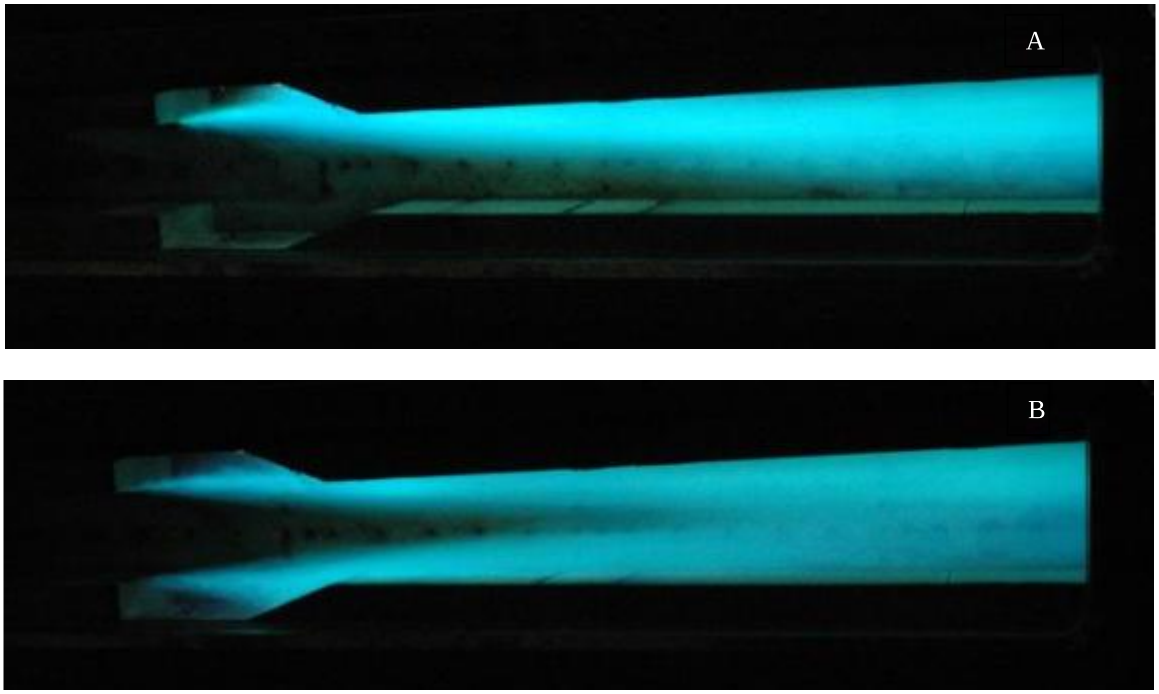

Figure 19A and 19B. Digital photographs of combustion. A: I-2 fueling only; B: I-2 and I-4 fueling**.**

Figure 19A is a photograph of combustion taking place with only I-2 fueling and an equivalence ratio of 0.61. The photograph in Figure 19B has an equivalence ratio of 0.69 split equally between I-2 and I-4. The bottom image shows combustion occurring in both cavities. These photographs give a better understanding of the combustion process and can verify when combustion is taking place in each of the cavities. The difference between top-only and top and bottom cavity fueling is clearly shown. However, there are limitations to what can be understood from this type of photograph. The images show illumination of the combustion across the entire flow path. The flame may be only near the combustor walls with a cold core. There is no way to tell at exactly what location in the flow the combustion is occurring since it is line-of-sight. These images clearly show the dual cavity allows for a significant increase in combustion and therefore provides greater heat release and improved performance.

IV. Conclusions

The main objective of this study was to investigate the dual cavity performance and to determine the advantages and disadvantages of using a dual cavity versus a single cavity flame holder. This objective was accomplished by studying wall pressures, pressure ratios, stream thrusts, numerical assessments, and visualization.

Peak pressure and combustor exit pressures were studied and the dual cavity consistently showed higher ratios for both. The increase in pressure is a result of additional heat being released from the combustion. This result suggests the dual cavity flow path provides better combustion and performance than the single cavity.

Stream thrust was the second performance parameter studied. Each case showed a stream thrust significantly higher for the dual cavity than for the single cavity. The dual flow path had an average of 72% higher values over all of the cases. The increase of stream thrust with the dual cavity is further evidence that adding the additional flame holder provides better performance.

This study also aimed to investigate the operability of the dual cavity flow path over a range of equivalence ratios and fuel injection schemes. For similar fueling conditions, each run with the dual cavity configuration had a shock position further upstream in the isolator than the single cavity flow path. However, the superiority of the dual cavity configuration was demonstrated by the downstream shock position and higher levels of stream thrust that were obtained by varying fueling conditions. The dual cavity also required less fuel to achieve the same stream thrust as compared with the single cavity.

The single cavity flow path has been more extensively studied in the past and is known to provide sufficient combustion under most conditions. This research verified operability of the single cavity flow path between

equivalence ratios of approximately 0.53 to 0.95. The operability window of the dual cavity flow path was smaller than that of the single cavity as the equivalence ratio was increased. However, the dual cavity provided increased overall performance shown by the stream thrust and pressure ratio results. The analysis conducted in this study suggests the dual cavity flame holder flow path provides significant advantages over the baseline and would be a viable option for future scramjet engines.

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